LABORATORY BASED HIGH ENERGY ASTROPHYSICS

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- Introduction
- Universe as a Laboratory
- Three Categories of High Energy Laboratory Astrophysics
- Calibration of Observations
- Investigation of Astro-Dynamics
- Probing Fundamental Physics
- Summary

Advanced Proton Driver Workshop, Fermilab, Oct. 6-8, 2004

National Research Council Turner Committee

Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century

Laboratory Astrophysics can address several of these basic questions:

- **How do cosmic accelerators work and what are they accelerating?**
- **Are there new states of matter at exceedingly high density and temperature?**
- **Are there additional space-time dimensions?**
- **Did Einstein have the last word on gravity?**
- **Is a new theory of matter and light needed at highest energies?**

One of the seven recommendations made by the Turner Committee:

Recommendation On Exploring Physics Under Extreme Conditions In The Laboratory
"Discern the physical principles that govern extreme astrophysical environments through the ***laboratory study*** *of high energy-density physics. The Committee recommends that the agencies cooperate in bringing together the different scientific communities that can foster this rapidly developing field."*

We are here to acquaint you with how a DOE facility can play a major role.

Connection to Extreme Astrophysical Conditions

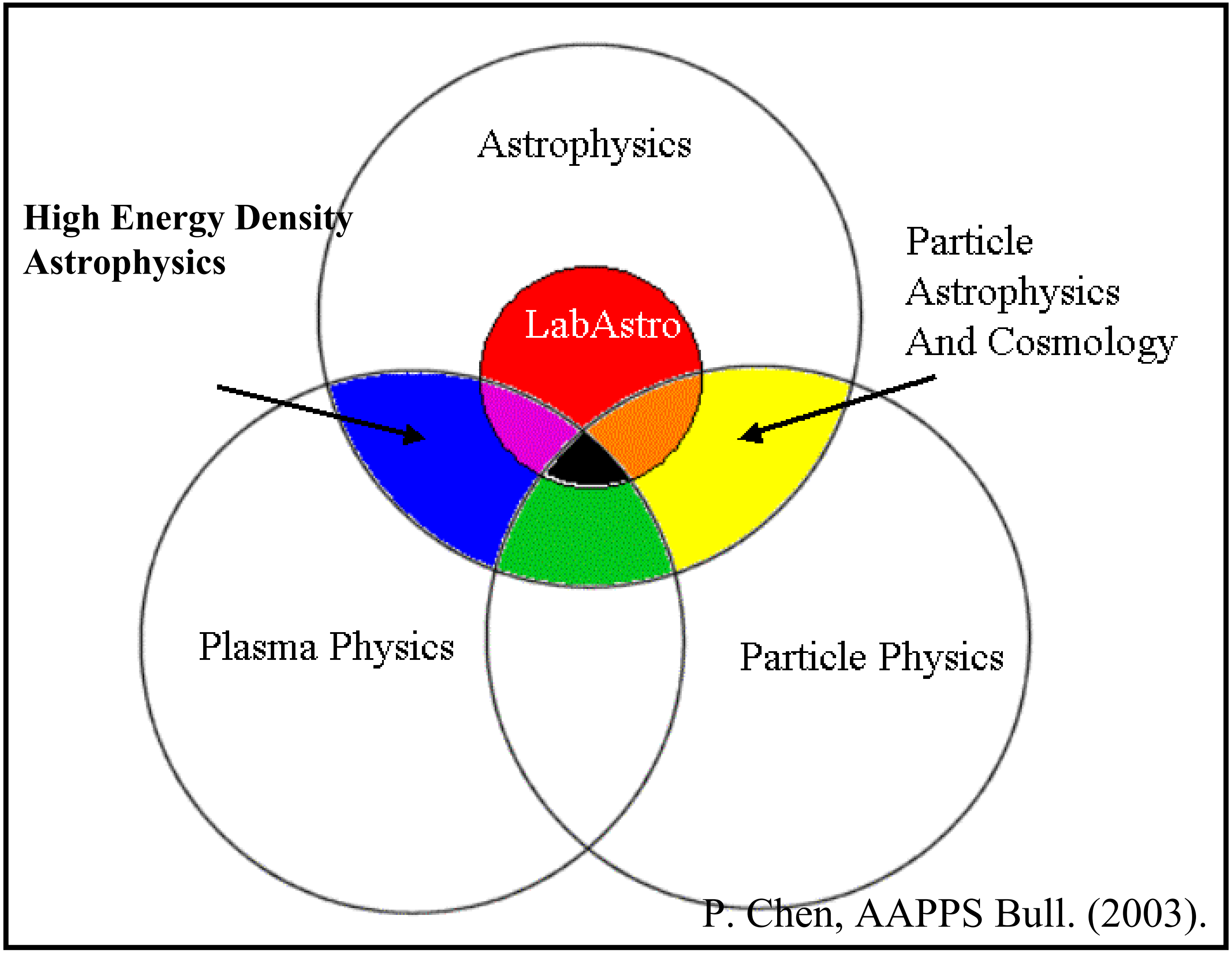
- Extremely high energy events, such as ultra high energy cosmic rays (UHECR), neutrinos, and gamma rays
- Very high density, high pressure, and high temperature processes, such as supernova explosions and gamma ray bursts (GRB)
- Super strong field environments, such as that around black holes (BH) and neutron stars (NS)

NRC Davidson Committee Report (2003) "**Frontiers in High Energy Density Physics**" states:

*"Detailed understanding of acceleration and propagation of the highest-energy particles ever observed demands a **coordinated effort** from plasma physics, particle physics and astrophysics communities"*

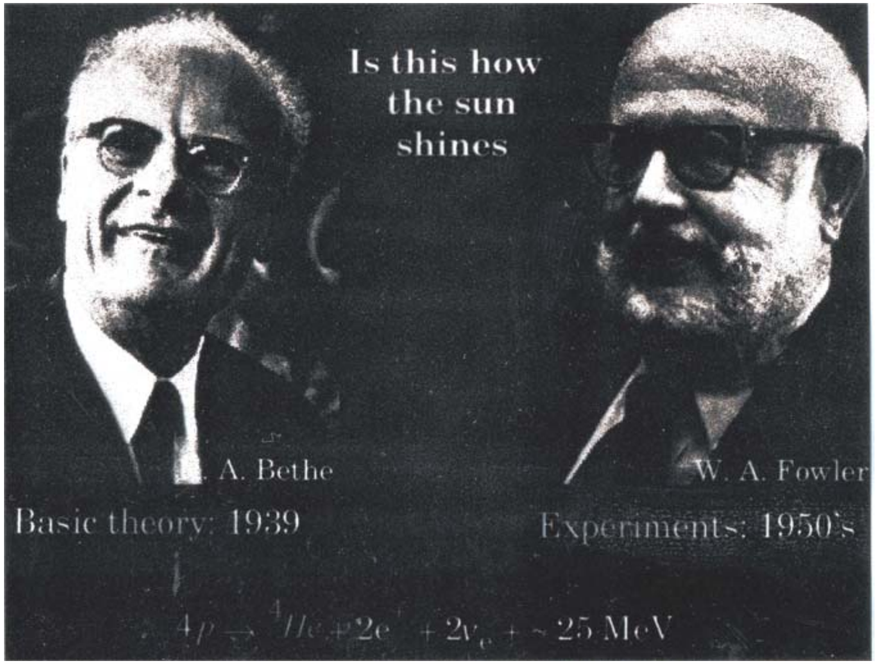
LABORATORY ASTROPHYSICS

Its relationship with Astrophysics, Particle Physics, and Plasma Physics



Symbiosis between Direct Observations and Laboratory Investigations

Classic example: Laboratory determination of stellar evolution



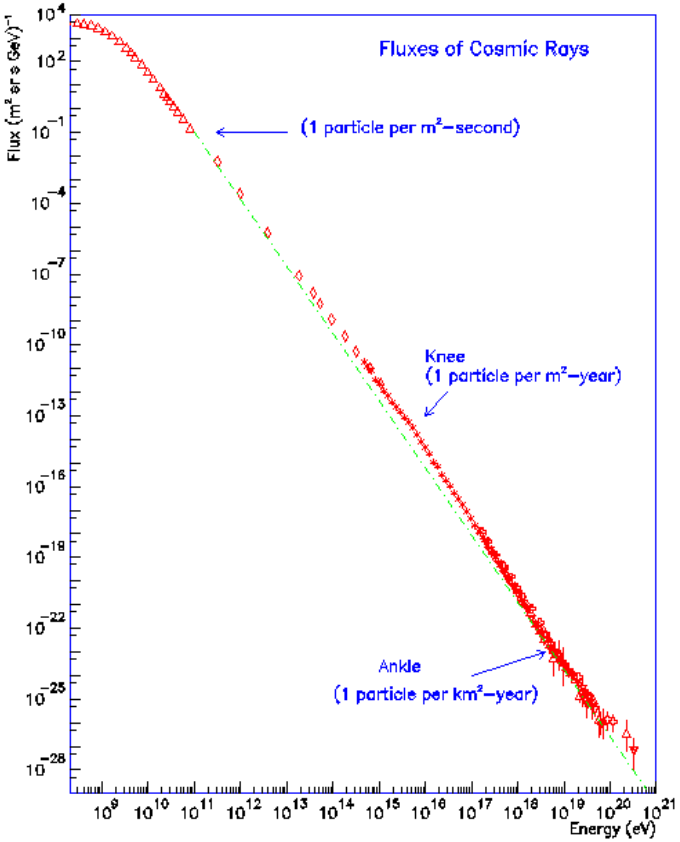
$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e + \sim 25 \text{ MeV}$$

Symbiosis should still be true for Particle Astrophysics and Cosmology

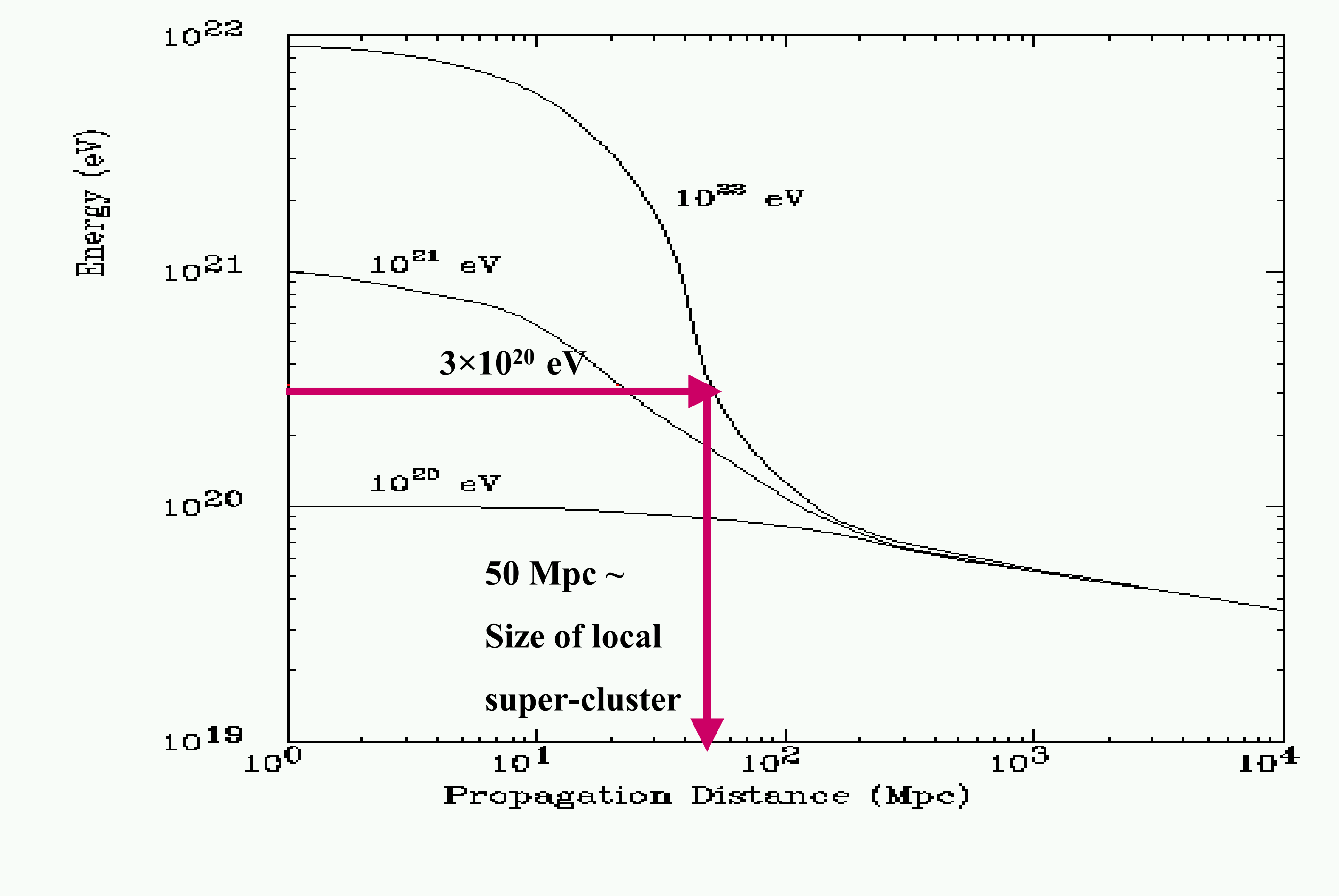
UNIVERSE AS A LABORATORY
- Extremely High Energy Events -

- Ultra High Energy Cosmic Rays (UHECR)
  - "Knee" and "ankle" in UHECR spectrum
  - Events beyond GZK-limit found
- Very high energy ν's and γ's
  - ν masses and oscillations
  - Extremely high energy γ: violation of Lorentz invariance?

"Is a new theory of matter and light needed at the highest energies?"



Greisen-Zatsepin-Kuzmin Limit



- Protons above 6×10^{19} eV will lose sizable energy through CMB
- Super-GZK events have been found with no identifiable local sources

Cosmic Acceleration Mechanisms

- Conventional cosmic acceleration mechanisms encounter limitations:

  - Fermi acceleration (1949) (= stochastic accel. bouncing off B-fields)

  - Diffusive shock acceleration (70s) (a variant of Fermi mechanism)

  Limitations for UHE: field strength, diffusive scattering inelastic

  - Eddington acceleration (= acceleration by photon pressure)

  Limitation: acceleration diminishes as $1/\gamma$

- New thinking:

  - Zevatron (= unipolar induction acceleration) (R. Blandford)

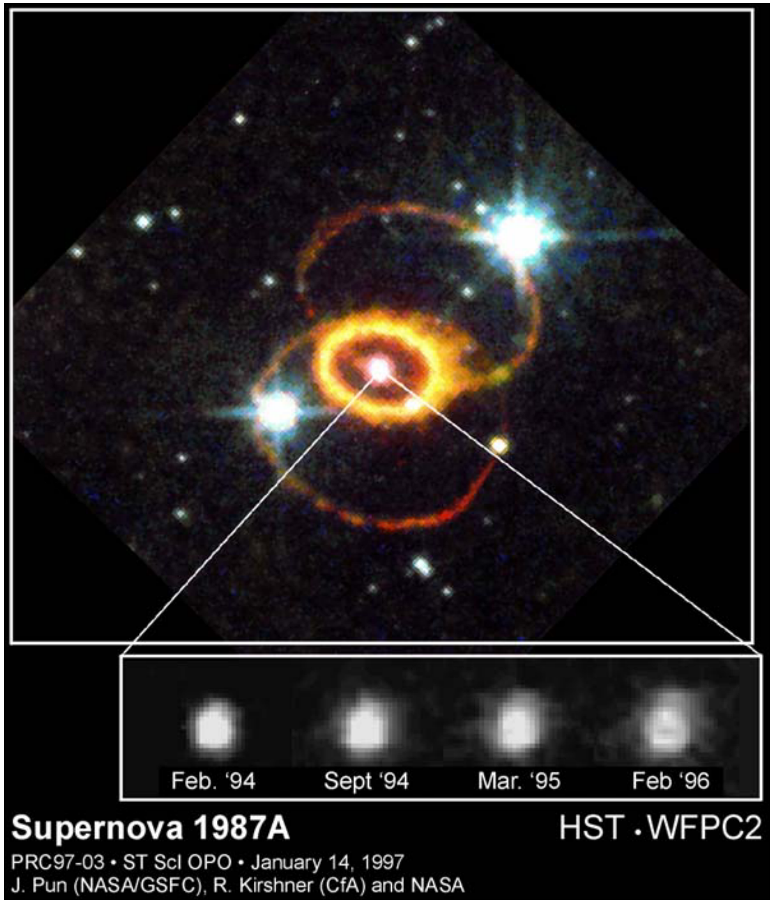
  - Alfven-wave induced wakefield acceleration in relativistic plasma

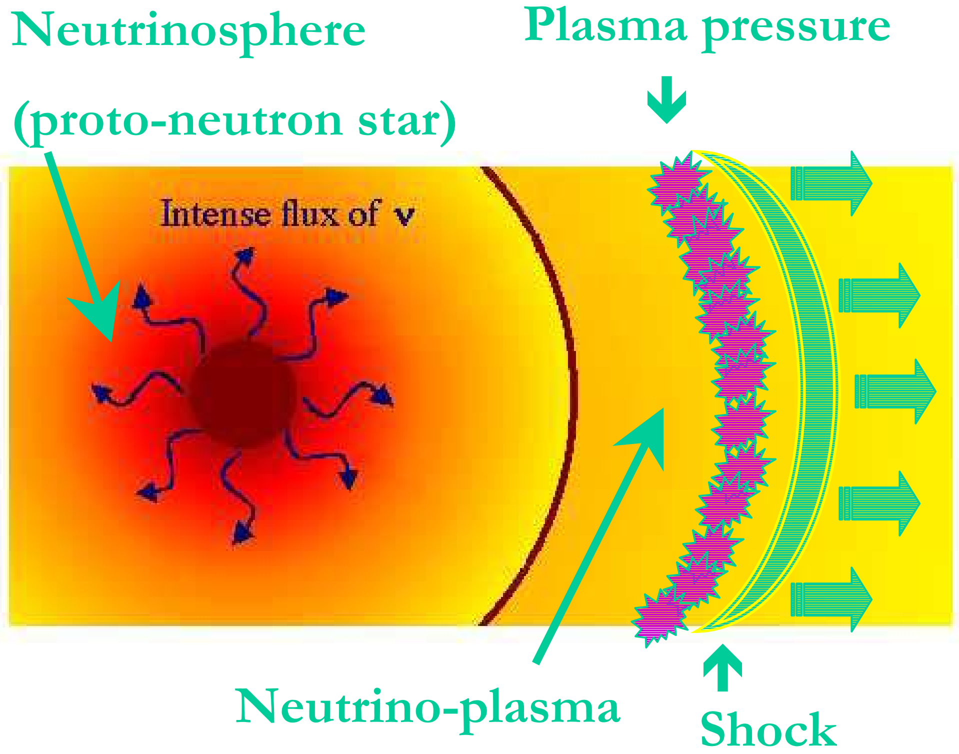
  (Chen, Tajima, Takahashi, Phys. Rev. Lett. <u>89</u> , 161101 (2002).)

  - Additional ideas by M. Barring, R. Rosner, etc.

UNIVERSE AS A LABORATORY
- Ultra High Energy-Density Processes -

• Supernova explosion



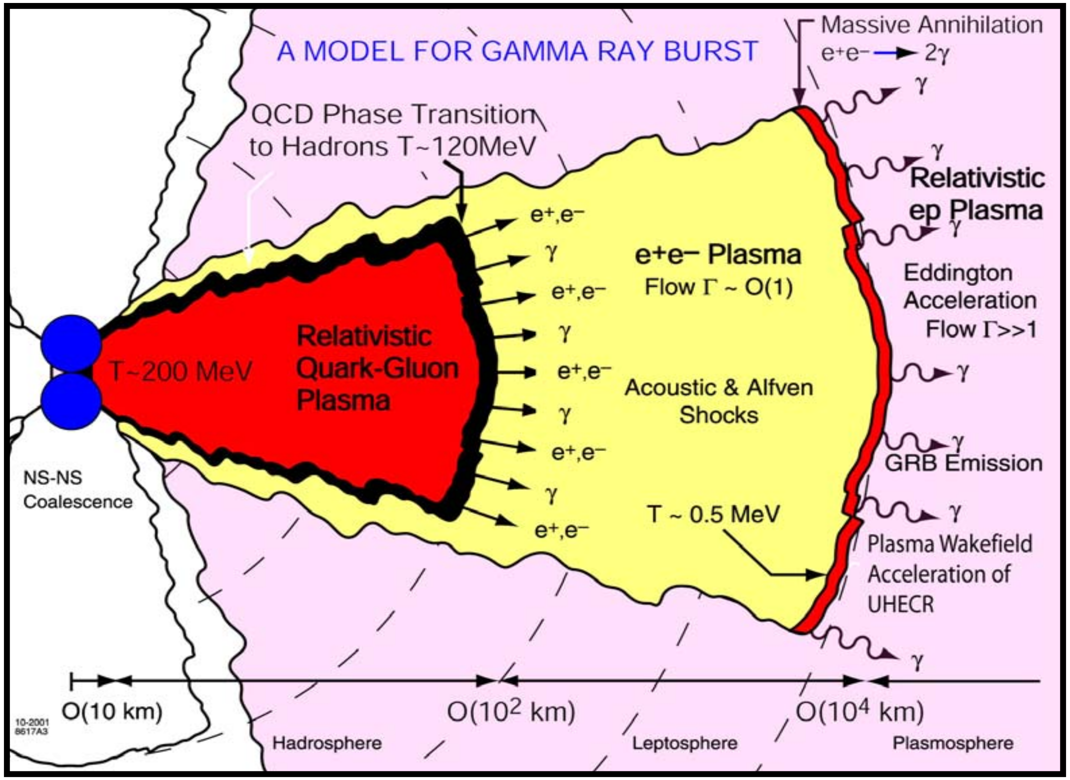


Bingham, Dawson, Bethe,
Phys. Lett. A, 220, 107 (1996)

Phys. Rev. Lett., 88, 2703 (1999)

Gamma Ray Burst

- Release of ~ 10^{52} erg/sec (short bursts)!
- "Standard" relativistic fireball model (Rees-Meszaros, 92, 93)
- Extended model invokes quark-gluon plasma (Chen et al., 01)



"Are there new states of matter at exceedingly high density and temperature?"

UNIVERSE AS A LABORATORY
- Super Strong Field Environment -

- Black holes and strong gravitational field
  - Testing general relativity
  "Did Einstein have the last word on gravity?"
- Neutron stars and strong EM fields
  - Schwinger critical field: $B_c \sim 4\times10^{13}$ G or $E_c \sim 10^{16}$ V/m
  - QED Vacuum unstable

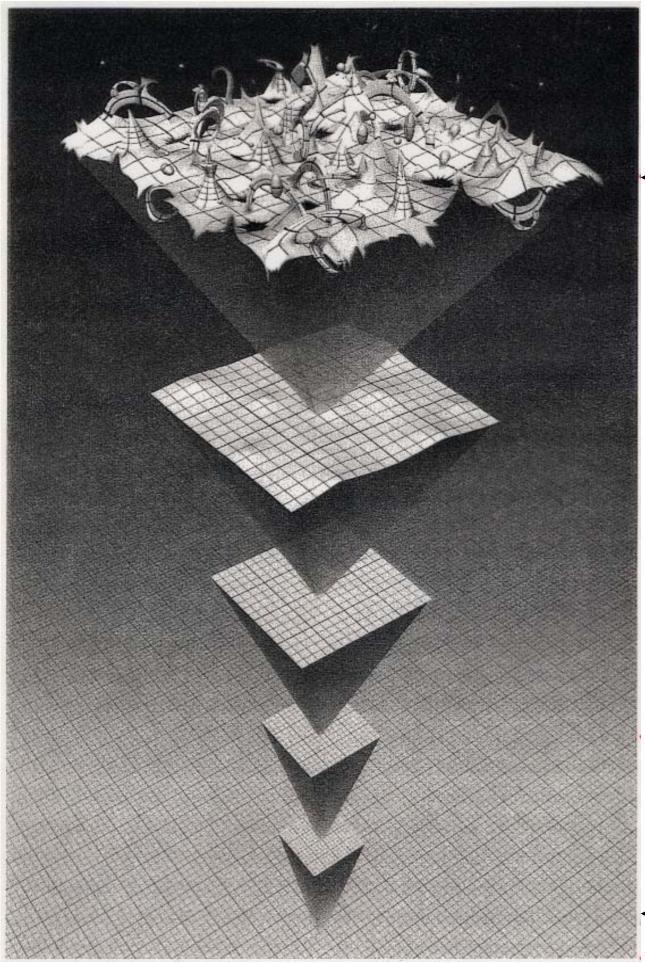
UNIVERSE AS A LABORATORY
- Extreme Limits of Spacetime and Vacuum -

- ~2/3 of the present energy density of the universe is in "dark energy".

"What is the nature of dark energy?"

- Quantum effects of gravity becomes sizable, or spacetime becomes unrest, at Planck scale.

"Are there additional spacetime dimensions?"



Planck scale $\sim 10^{-35}$m

Human scale $\sim$ 1m

Three Categories of LabAstro

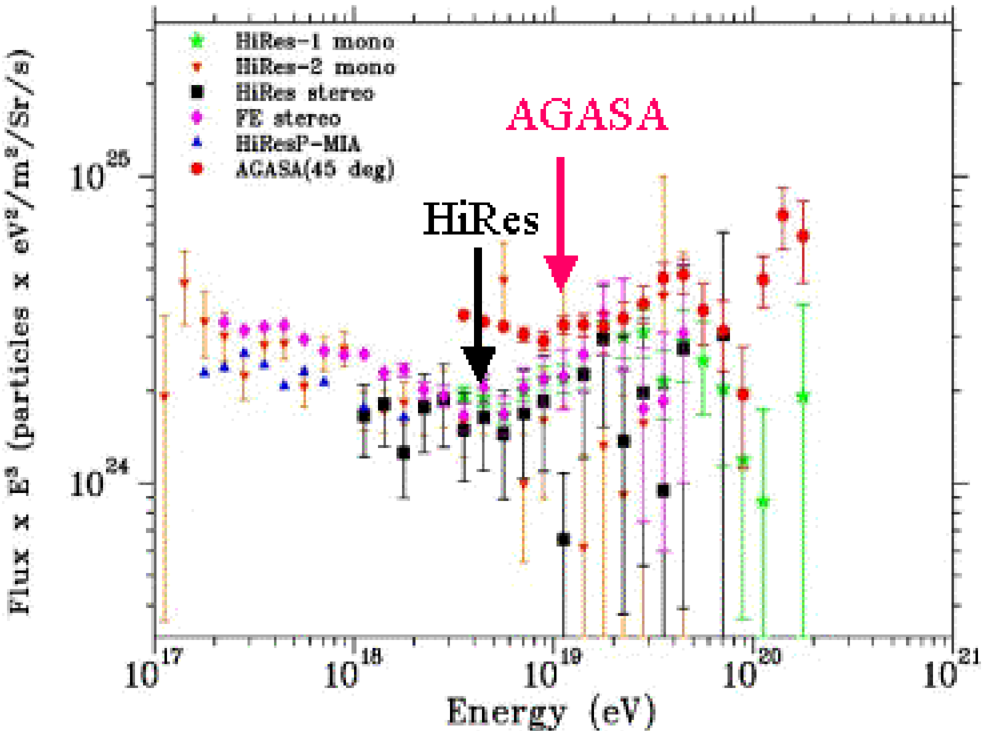
-Using Lasers and Particle Beams as Tools -

1. Calibration of observation
   - Precision measurements to calibrate observation processes
   - Development of novel approaches to astro-experimentations
   - Though mundane, value to astrophysics most certain
2. Investigation of Astro-dynamics
   - Astro-conditions hard to recreate in lab
   - Many MHD or plasma processes scalable by extrapolation
   - Value lies in revelation of dynamical underpinnings
3. Probing fundamental physics
   - Underlying physical principles may yet to be developed
   - Extreme limits render signatures faint; viability uncertain
   - Issues at stake too fundamental to be ignored for experimentation

CALIBRATION OF OBSERVATIONS

Motivation for FLASH

- Apparent Discrepancy in the UHECR spectrum



- ➢Systematics in the fluorescence yield?
- ➢How well is the shower lateral profile understood?
- ➢Impact on future experiments: Auger, OWL, EUSO, etc..

A shower experiment using SLAC beams.

Current LabAstro Experiment at SLAC

*FL*uorescence from *A*ir in *SH*owers (FLASH: SLAC E-165)

J. Belz[1], Z. Cao[2], P. Chen[3]*, C. Field[3], P. Huentemeyer[2], W-Y. P. Hwang[4], R. Iverson[3], C.C.H. Jui[2], T. Kamae[3], G.-L. Lin[4], E.C. Loh[2], K. Martens[2], J.N. Matthews[2], W.R. Nelson[3], J.S.T. Ng[3], A. Odian[3], K. Reil[3], J.D. Smith[2], P. Sokolsky[2]*, R.W. Springer[2], S.B. Thomas[2], G.B. Thomson[5], D. Walz[3]

1. University of Montana, Missoula, Montana
2. University of Utah, Salt Lake City, Utah
3. Stanford Linear Accelerator Center, Stanford University, CA
4. Center for Cosmology and Particle Astrophysics (CosPA), Taiwan
5. Rutgers University, Piscataway, New Jersey

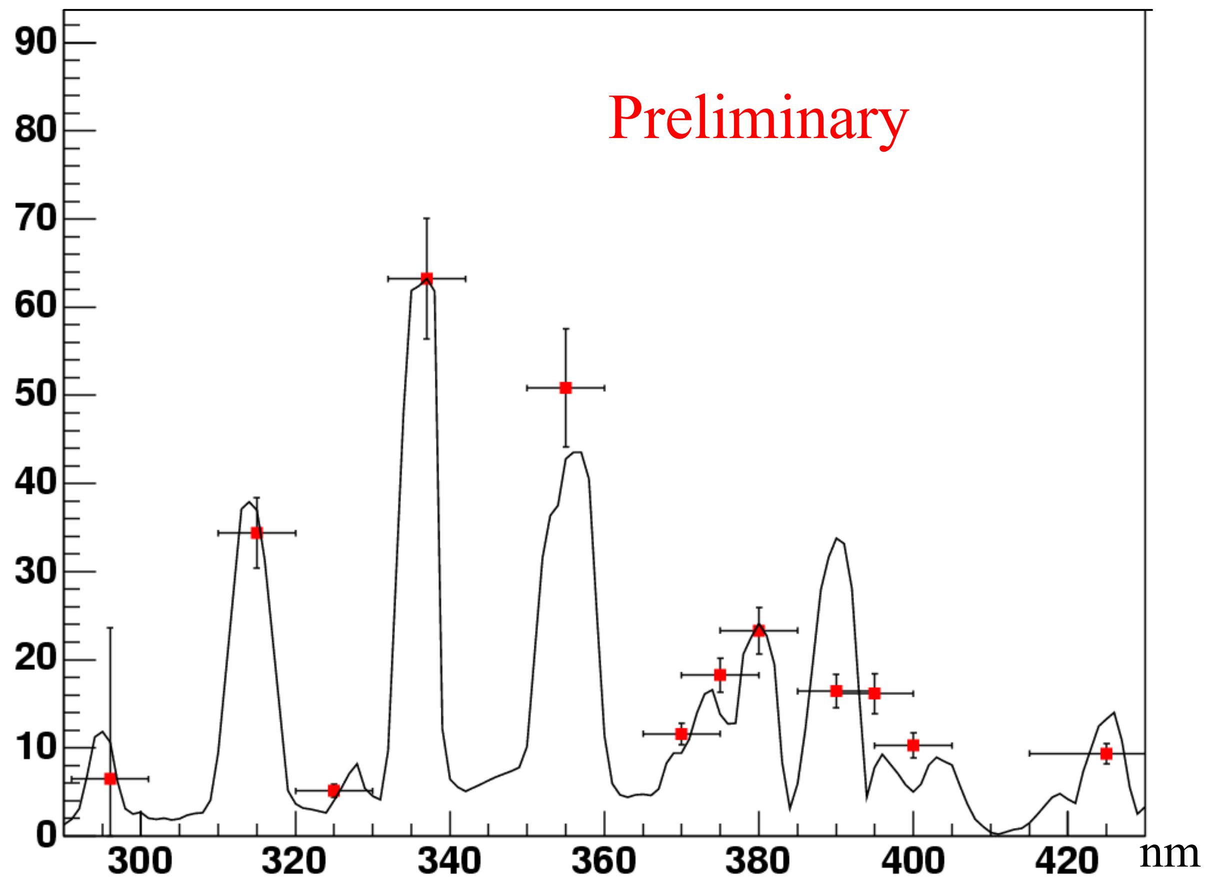
* Collaboration Spokespersons

SLAC E-165 Experiment
Fluorescence in Air from Showers (FLASH)

HiRes-SLAC-CosPA (Taiwan) collaboration

Thin Target Results

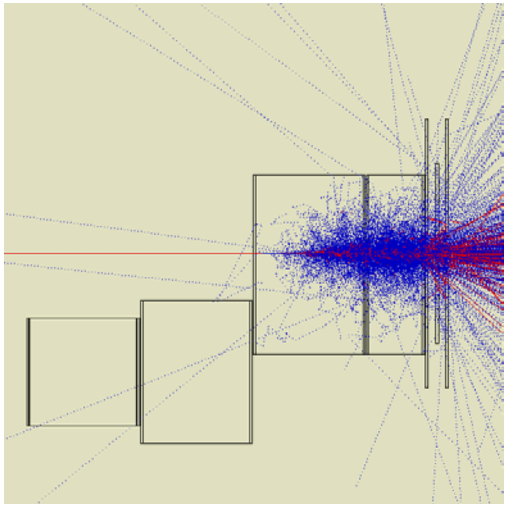
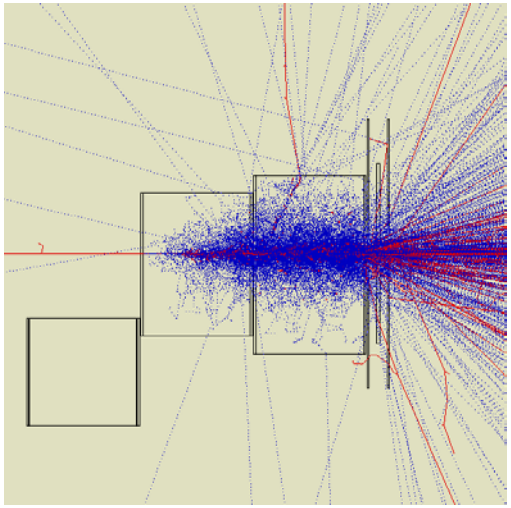
- Vertical scale is arbitrary (absolute yield awaits opitcal calibration: almost complete)
- Overlaid with Spectrum from A. Bunner (1967)



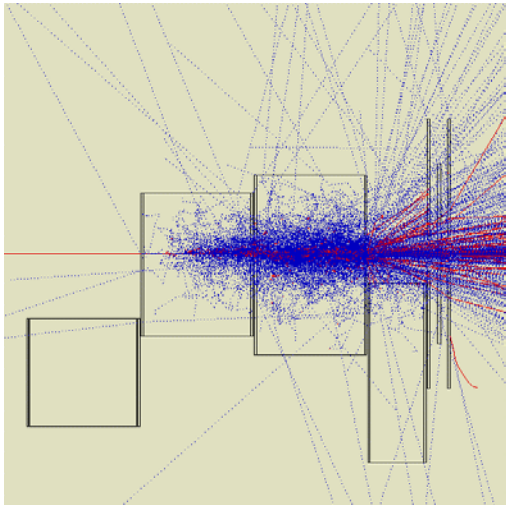
Thick Target Setup

Shown with about 50% of lead shielding in place (shilding from gamma rays and neutrons)

Need to Simulate Details!

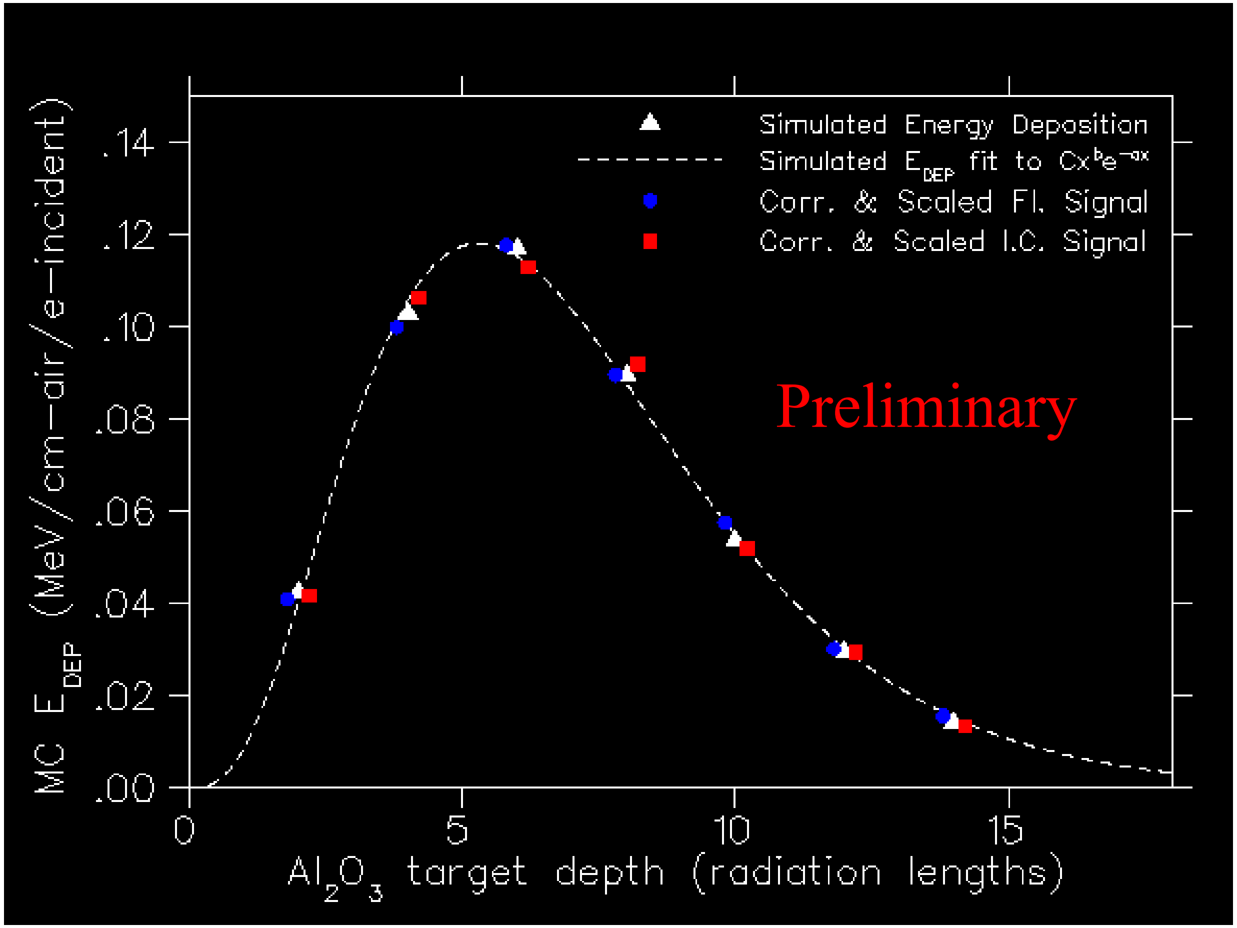
- Idealized Simulation of 6 and 8 R. L.



- Simulation of actual setup for 8 R. L. (also for 4, 12)

FLASH Shower Data:
Fluorescence and Charged Particles Correlated

- Absolute calibration of optical system and ion chamber in progress
- Also used diamond detector to measure lateral profile



INVESTIGATION OF ASTRO-DYNAMICS

Length Scales

← **Compton Scale**
HEP

MHD Scale →
Shocks

Compton Wavelength of the proton ~ 13x10^{-14} cm

~10^8 cm

Plasma scale

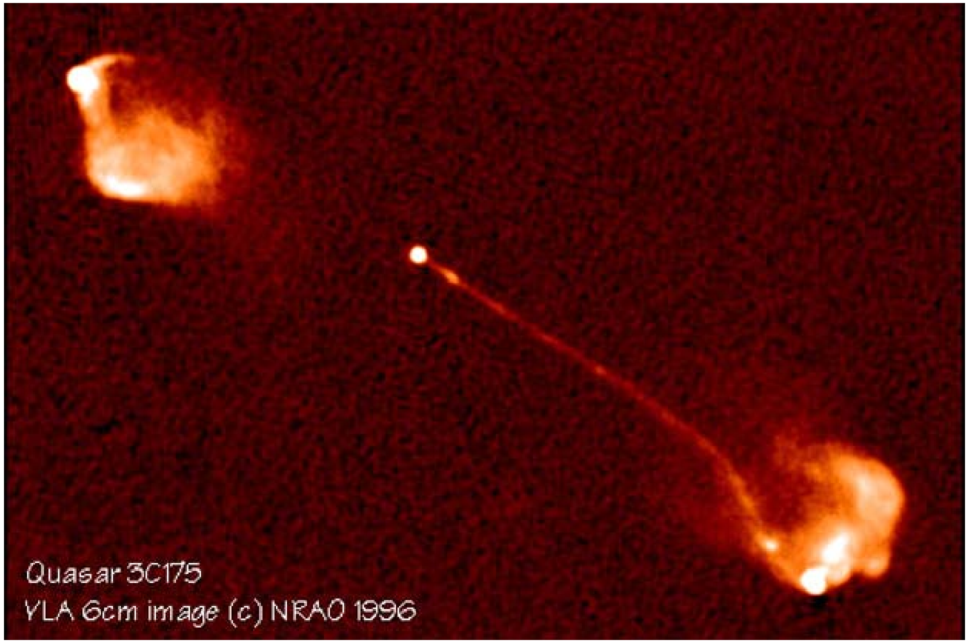
λ_D, λ_p, r_L

Spanning 20 orders of magnitude

Plasma dynamics scalable from the astrophysical dimensions to laboratory dimensions

Relativistic Plasma Experiments using Particle Accelerator Beams

- High energy astrophysics phenomenon involve interactions of relativistic (bulk $\Gamma >> 1$) plasma with ambient plasma, for example:
  - GRB: colliding plasma shells
  - AGN jets: bow-shocks



- Strong non-linear dynamics can produce:
  - highly non-thermal radiation
  - particle acceleration – perhaps even ultra-high energy cosmic rays.

Complement observations with insights into underlying dynamics obtained from controlled laboratory experiments.

Relativistic Plasma Experiments using Particle Accelerator Beams

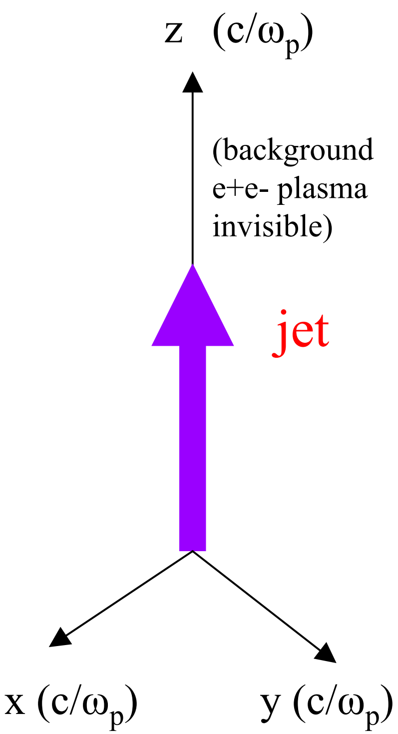
- Particle beam: a high-energy-density system that exhibits strong nonlinear, collective behavior
  - plasma acceleration and focusing, for example.
- APD beam parameters yield 40 PW of pulse power with 10^{20} W/cm^2 intensity
  - the energy density is very high: 10^{13} J/m^3
- Experiments to investigate relativistic plasma dynamics relevant for GRBs and AGN jets
  - radiation properties and particle acceleration mechanisms

➡ Possible experiments and parameters

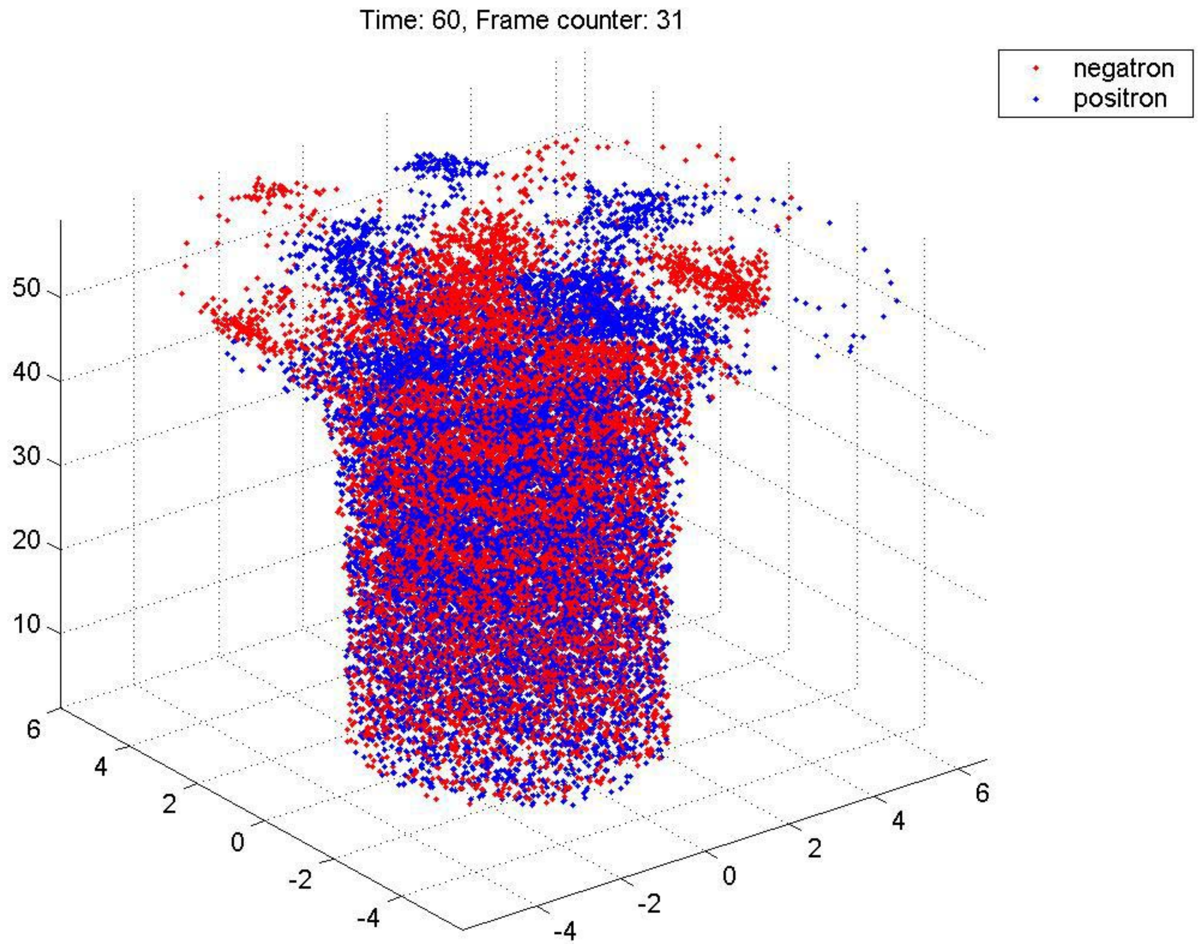
➡ Simulations and unresolved issues

[J.S.T. Ng, SLAC-PUB-10134; Astro-ph-2003]

3D PIC Simuation (TRISTAN): e+e- jet, Γ =40, jet/plasma density = 10



1 out of 16 jet particles plotted

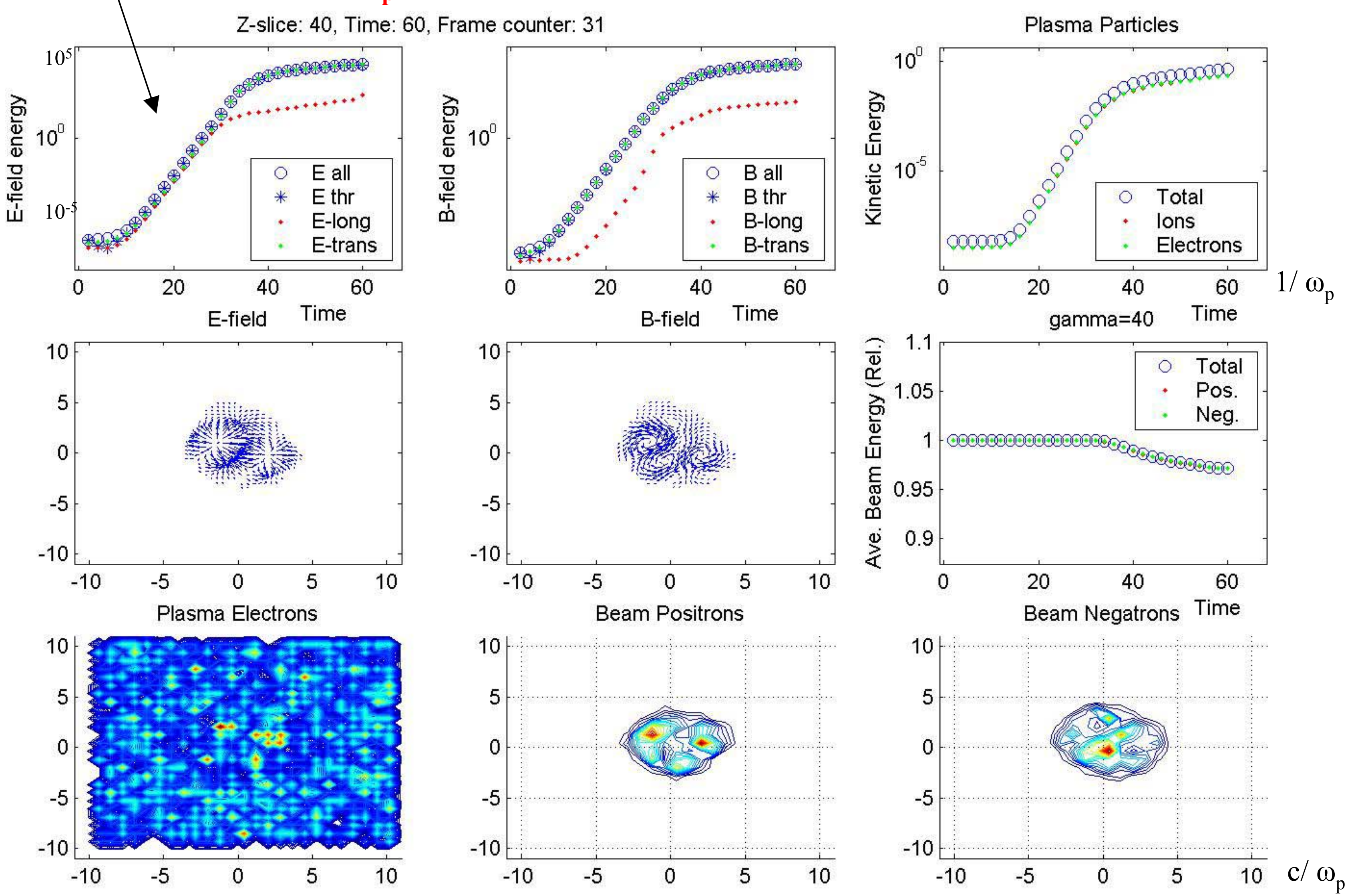


A "fountain" of plasma dynamics

[R.Noble and J.Ng, ARDB Seminar, Sep.29,2004]

CASE: Γ =40, Jet/Plasma Density = 10

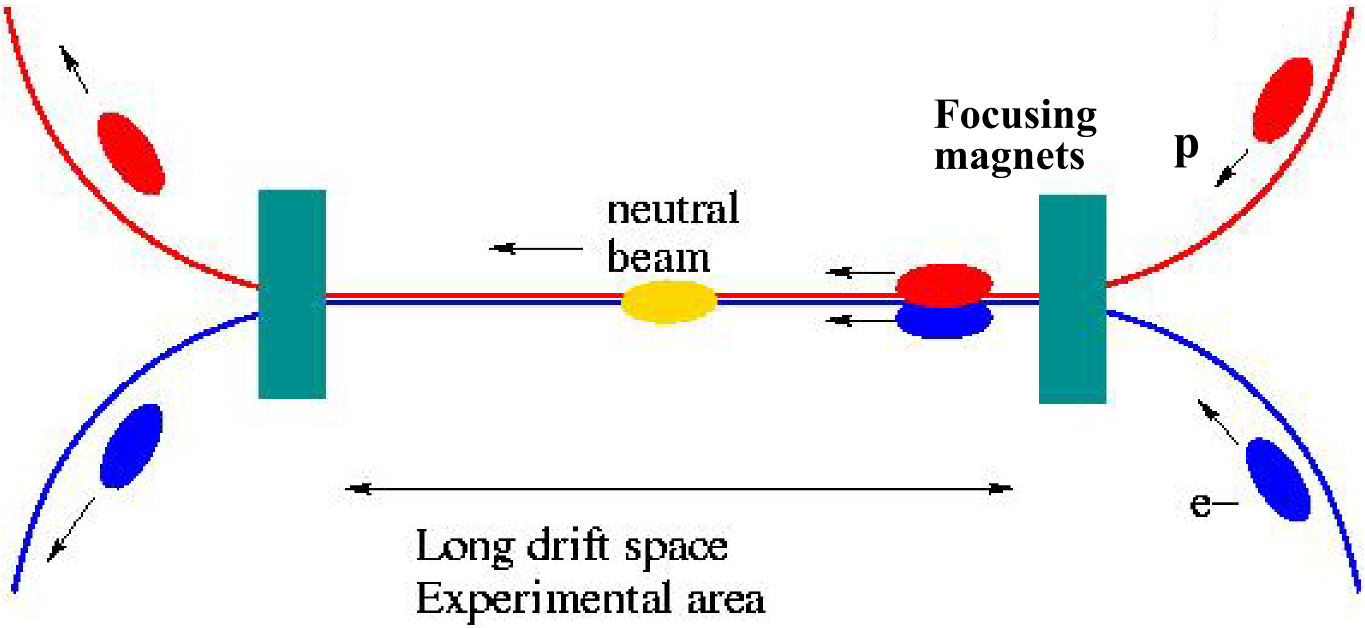
Growth rate:
$E^2 \sim \exp(2t/\tau) \rightarrow 1/\tau \approx 0.42\ \omega_p$



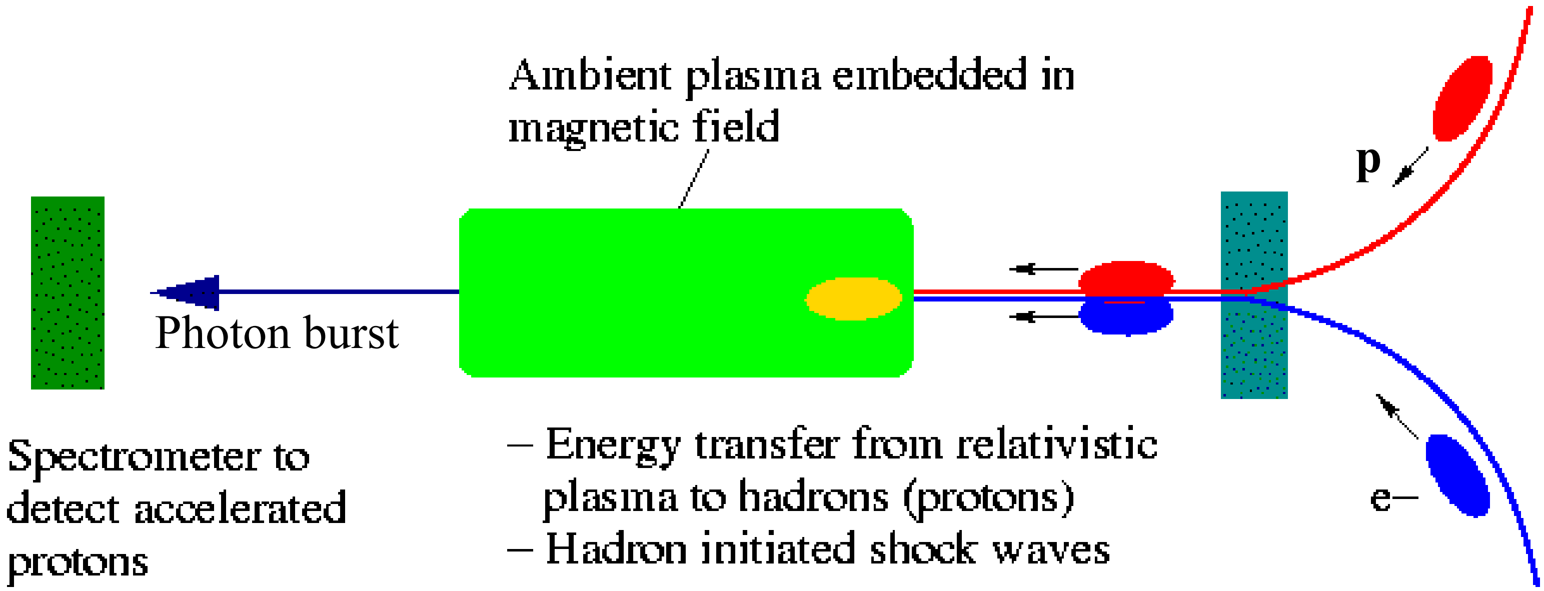
[R.Noble and J.Ng, ARDB Seminar, Sep.29,2004]

Relativistic ep Plasma Created Using APD Beams

Basic idea: merge an electron beam and a APD proton beam in space and time to produce a relativistic plasma.



Relativistic Jet-Plasma Interaction: Acceleration and Radiation

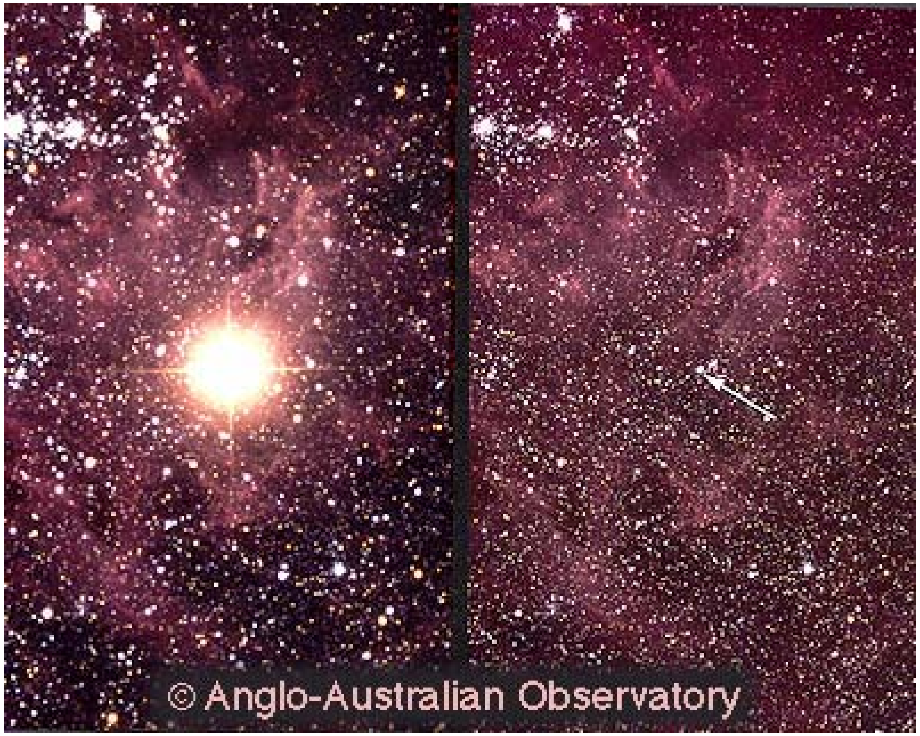


➢ **Test Models for AGN Jets and GRB Fireballs and cosmic ray acceleration mechanisms**

Neutrino Plasma Astrophysics

Can intense neutrino winds drive collective and kinetic mechanisms at the *plasma scale* ?

(Bingham, Bethe, Dawson & Su, 1994)



Neutrinos repel nearby electrons - Dressed neutrino with equivalent electric charge, a fraction of the electron charge

$\Rightarrow$ ***Effective neutrino charge,*** $\mathbf{e}_\nu$

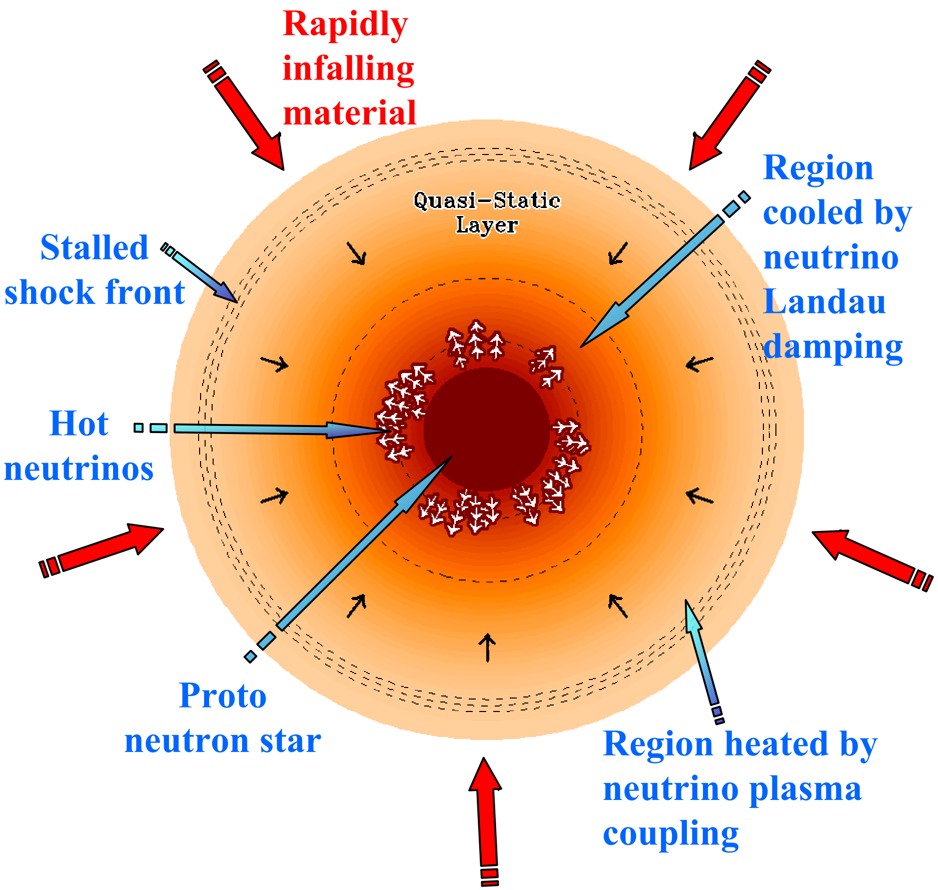
$$e_\nu \approx -\frac{\sqrt{8}\pi}{k_B T_e} G_F n_{e0} e$$

Supernova Electroweak Plasma Instability

• 99% of SN energy is carried by neutrinos from the core

• Single-particle dynamics unable to explain explosion

• ν-flux induced collective electroweak plasma instabilities load energy to plasma efficiently*



To form a neutron star 3×10^{53} erg must be released
(gravitational binding energy of the original star)
• light+kinetic energy ~ 10^{51} erg •
• gravitational radiation < 1% •

* Bingham, Dawson & Bethe, Phys. Lett. A, 220, 107 (1996), Phys. Rev. Lett., 88, 2703 (1999)

Plasma Waves Driven by Electrons, Photons, and Neutrinos

Equations for electron density perturbation driven by electron beam, photon beam, neutrino beam, are similar:

Electron beam

$$\left(\partial_t^2 + \omega_{pe0}^2\right)\delta n_e = -\omega_{pe0}^2 n_{e-beam}$$

Photons

$$\left(\partial_t^2 + \omega_{pe0}^2\right)\delta n_e = \frac{\omega_{pe0}^2}{2m_e}\nabla^2 \int \frac{d\mathbf{k}}{(2\pi)^3}\hbar \frac{N_\gamma}{\omega_{\mathbf{k}}}$$

Neutrinos

$$(\partial_t^2 + \omega_{pe0}^2)\delta n_e = \frac{\sqrt{2}n_{e0}G_F}{m_e}\nabla^2 n_\nu$$

where δn_e is the perturbed electron plasma density

- **Similar to *e*-beam induced two-stream instability, Landau damping, and Weibel instability**

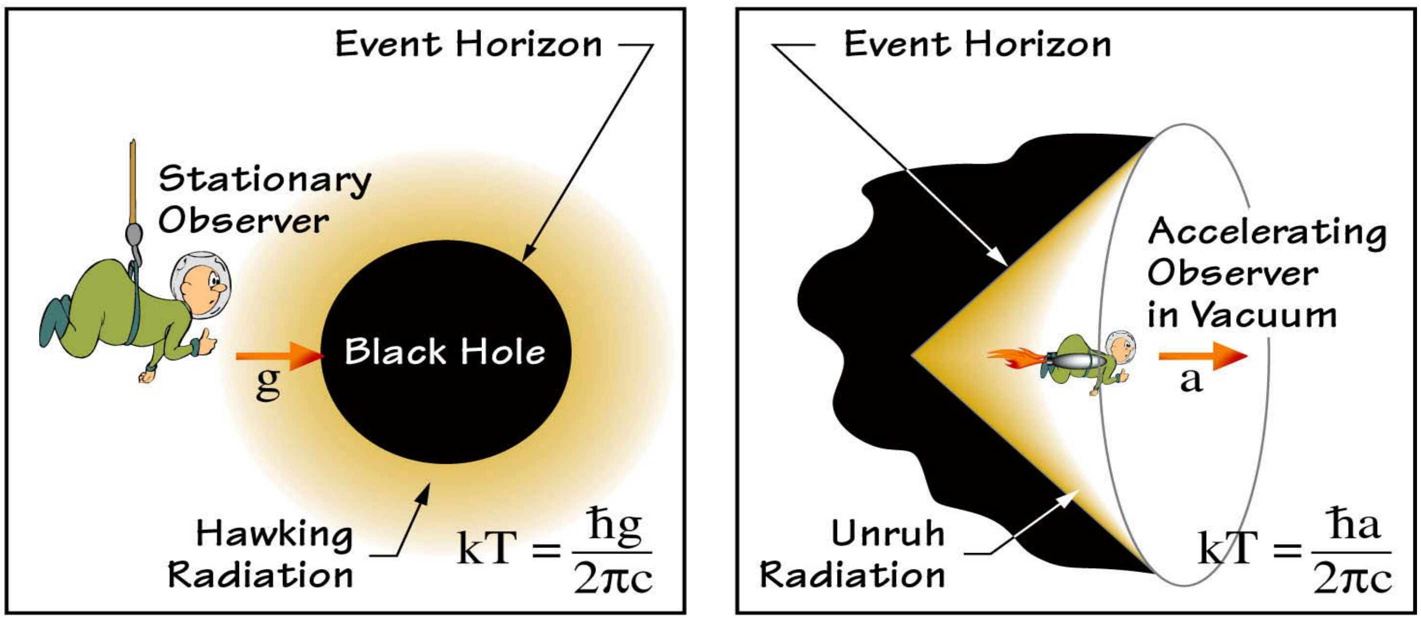
Using intense ν-beams from APD to investigate SN puzzle!?

PROBING FUNDAMENTAL PHYSICS

Probing Event Horizon

(Chen and Tajima, 1999)

EVENT HORIZONS: From Black Holes to Acceleration



A stationary observer outside the black hole would see the thermal Hawking radiation.

An accelerating observer in vacuum would see a similar Hawking-like radiation called Unruh radiation.

5-2000
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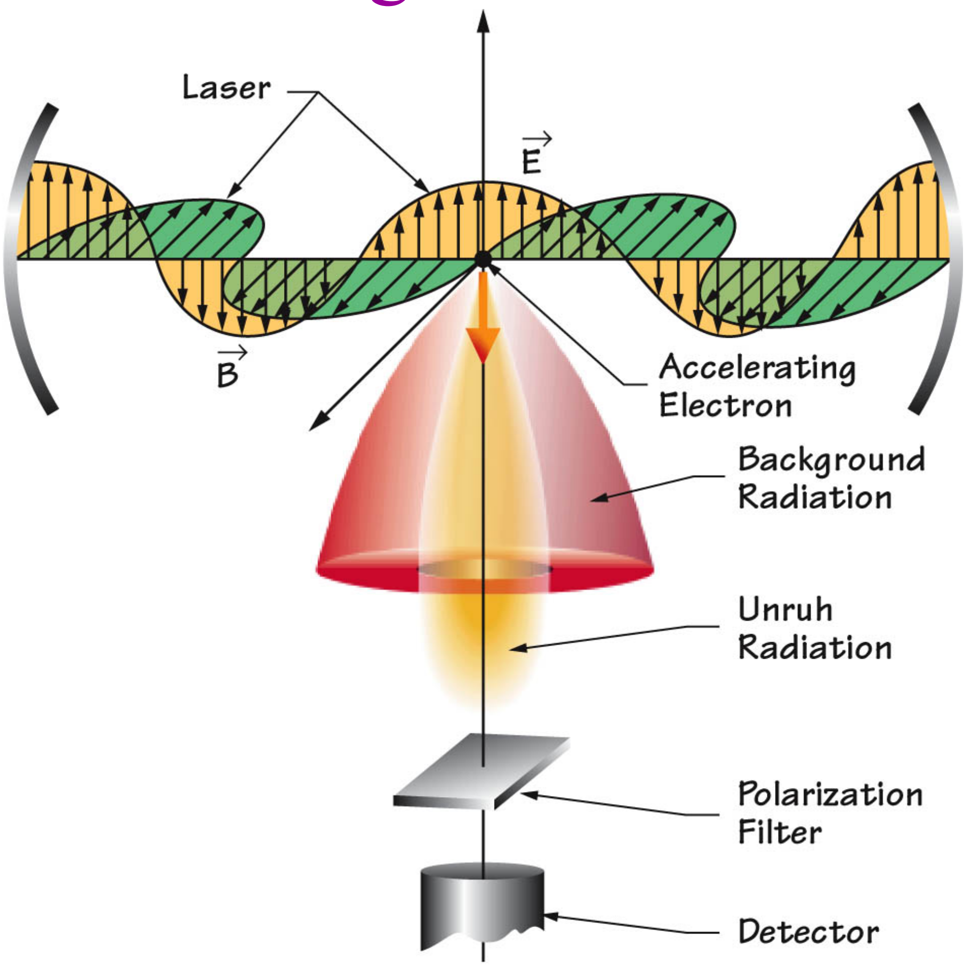
A Conceptual Design of an Experiment for Detecting the Unruh Effect



Schematic Diagram for Detecting Unruh Radiation

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Probing Extra Dimensions via Violent Acceleration

- In standard theory of gravity, the Planck scale is at

  $M_p \sim 10^{19}$ GeV, or $L_p \sim 10^{-33}$ cm.
- Inside large extra dimensions with radius R ($\gg L_p$), gravity is ***stronger***:

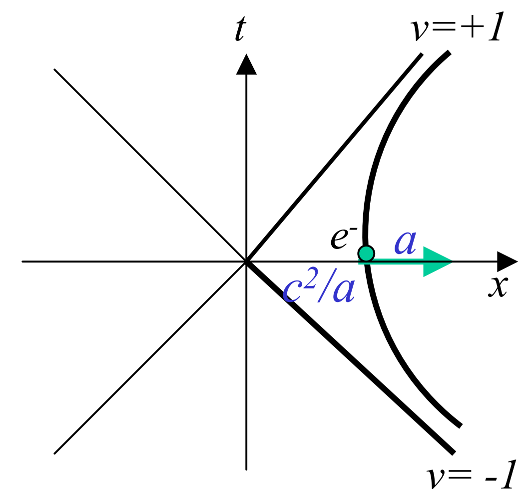
  $F = GmM/r^{2+\mathrm{n}}$.
- This gives rise to a smaller effective Planck scale M_* , where

  $R \sim (M_p/M_*)^{(\mathrm{n}+2)/\mathrm{n}} L_p$.
- To solve the "hierarchy problem", one identifies M_* with the electroweak scale (~ TeV), then

  $R \sim 10^{32/\mathrm{n}\,-\,17}$ cm. (e.g. for n=6, $R \sim 10^{-12}$ cm)
- Distance from accelerating electron to the event horizon,

  $d \sim c^2/a$;

  This can probe extra spacetime dimensions to this scale.



***State-of-the art laser to accelerate electrons can probe up to* n=3 (→ *R* ~ 10⁻⁶ cm).**

SUMMARY

- Revolutionary breakthroughs in *particle astrophysics and cosmology* have created new questions in physics at the most fundamental level.
- Many of these questions are directly connected with *high energy-density physics.*
- Laboratory experiments can address many of these important astrophysical issues.
- *Particle accelerators such as APD* are powerful tools for *laboratory astrophysics.*
- Three categories of LabAstro: *Calibration of observations, Investigation of dynamics,* and *Probing fundamental physics.* Each provides a unique value to astrophysics.